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STATUS REPORT ON THE LBL-SLAC PROTON-ELECTRON-POSITRON COLLIDING BEAM PROJECT

The LBL-SLAC Storage Ring Study Group

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The LBL-SLAC Storage Ring Study Group†

Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720

and

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

(Presented by A. M. Sessler)

ABSTRACT

The work of the joint LBL-SLAC study group on a proton-electron-positron colliding beam facility (PEP) is briefly described. Following a section on the physics which can be done on PEP, the guiding philosophy of the study is outlined, a first reasonably complete machine example is presented, and subjects which have been identified as requiring further study are delineated.

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† M. Allen (SLAC), J. Augustin (SLAC visitor from University of Paris, Orsay, France), R. Avery (LBL), A. Garren (LBL), E. Hartwig (LBL), D. Möhl (LBL visitor from CERN, Geneva, Switzerland), K. Neil (LBL participant from Lawrence Livermore Laboratory, Livermore, California), J. Rees (SLAC), B. Richter (SLAC), A. Sessler (LBL), L. Smith (LBL), H. Wiedemann (SLAC visitor from DESY, Hamburg, German Federal Republic).

I. INTRODUCTION

In June of 1971 a group of physicists from the Frascati Laboratory, CERN, the Lawrence Berkeley Laboratory, and the Stanford Linear Accelerator Center began a study of the feasibility of achieving a large reaction rate in very high energy electron-proton collisions through the use of colliding beam techniques. The results of this work were presented in a paper at the 1971 Accelerator Conference in Geneva,[1] which described a positron-electron-proton colliding beam complex, and the physics which could be done with such a facility.

In the fall of 1971 a joint LBL, SLAC study was organized whose first goal was a more thorough study of the physics potential of a high reaction rate electron-proton-colliding beam facility (the physics interest in the electron-positron component of the complex had been extensively investigated previously). The results of this study indicated that this type of colliding beam complex would vastly expand our horizons in the study of the structure and interactions of the elementary particles.[2]

1. Physics

The results of the physics study (Reference 2) were, briefly, that a high luminosity positron-electron-proton colliding beam complex (PEP) will be capable of an enormous extension of parameters in traditional electron machine experiments (inelastic electron scattering, photoproduction, etc.), and in addition will open the field of weak interactions to practical experimentation with a well-understood, well-controlled probe--the electron. In electron-positron collisions, PEP is capable of investigating particle production with a pure and beautifully simple photon probe at center-of-mass energies comparable to the highest-energy conventional accelerators now under construction.

In order to give the physics study a focus, the energies of the beams in PEP were chosen to be about 15 GeV for electrons and positrons, and 72 GeV for protons. This gives a center-of-mass energy for electron-proton collisions of 64 GeV which is the same as that which would be available if a 2000-GeV beam from a conventional accelerator strikes a stationary hydrogen target (there is no economically feasible way of reaching these energies with a conventional accelerator). The energy of 65 GeV in the c.m. is also in the same range as the ISR proton-proton machine of 50-GeV c.m. energy and also corresponds to the region where the weak interactions are expected to become comparable to the electromagnetic interactions. The 30-GeV c.m. energy available in electron-positron collisions matches the c.m. energy available in proton-proton collisions from a 500-GeV NAL. It should be emphasized that the detailed accelerator studies which will define the final parameters of a PEP device are in an early phase and still higher energies are under consideration.

It was found, in the physics studies, that a luminosity of 10^{32} cm^{-2} sec^{-1} is required in order to accomplish the wealth of interesting physics available at c-of-m energy 65 GeV.

2. Philosophy

For the first year, the accelerator study group has adopted the guiding philosophy of (1) addressing itself to fundamental technical questions concerning the PEP system, and (2) seeking a reasonable set of machine parameters. There is quite a large number of open questions, ranging from the specific to the general. Amongst the more general are: What are suitable beam energies for PEP? How can electron-proton and proton-proton rings be made compatible at a single installation without compromising the performance of either? Does PEP represent an unwise leap in parameters?

Amongst the more specific questions--and here we have partial answers, or at least active programs underway which soon should supply answers--are: What phase-space densities can be achieved for protons? How are the interaction regions designed? Is a large rf voltage required for the protons and if so, how is it supplied? What beam-collective phenomena limit performance, and what will be the lifetime of a bunched proton beam? To the extent that we have been able to develop information about these questions, the information has been incorporated into the design example of Section II. In Section III we discuss some of these questions and our present state of understanding and future program of research.

II. A MACHINE DESIGN EXAMPLE

In this section, we present the parameters for one reasonably complete example of a proton-electron-positron colliding-beam system. While we anticipate that the ultimate design may differ markedly from this example, we believe it to be worthy of study. The material of Sections II.1 and II.2 are taken from reference 3 by Garren.

1. General Input Considerations

The general scheme is the same as in Reference 1 in that all the particles in each ring are concentrated into a single short bunch. The proton bunch and the electron bunch collide every turn at low-β points in the two long insertions. In contrast to the system of Reference 1, the colliding beams here are co-linear, and the low-β values are somewhat larger. Table I gives the general parameters.

The proton beam is conceived as being injected from a booster with energy in the 3 to 6 GeV range and brightness equal to that of the CERN PS. It is then stacked in transverse phase space only (6 turns radially and 2 turns vertically), with a dilution factor of 1.35. The densities of both proton and electron beams are chosen to put the tune shifts at the "conventional" value of 0.025 in order to obtain maximum luminosity consistent with the incoherent limit. To take advantage of brighter proton beams or of longitudinal stacking requires consideration of non-zero crossing angles. The electron beam size is determined by the electron lattice parameters; therefore these have been chosen to produce the desired transverse dimensions. The number of electrons is $N_e = 3 \times 10^{12}$ for which the total radiated power is 2.8 MW, as in Reference 1. The number of protons, $N_p = 2 \times 10^{12}$, is modest. One could increase the number, but with this design the emittance would have to grow proportionately due to the electron beam-beam limit and little gain in luminosity could be achieved. If N_p is doubled, the magnet cross sectional area also doubles, but the luminosity only increases 15%. With the parameters of this note the luminosity is $\mathcal{L} = 0.57 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$.

2. Lattice Design

The electron-positron ring is taken to be in the same tunnel as the proton ring, and is situated 1.14m above the latter. The rings are in the form of a racetrack, with two semicircular arcs of about 200 mradius and two horizontally straight insertions about 330 m long. Vertical bending magnets in the insertion lead the beams to a co-linear interaction region in the center of the insertion. See Fig. 1. The separate electron-positron "dog legs" are used for e^-p or e^+p collisions respectively.

For e^+e^- collisions, both beams would traverse the same dog leg and the proton ring would be empty. The focussing in the electron insertion would be altered to lower the value of the β-function at the interaction point, β^*, for e^+e^- collisions. Between the arcs and the insertion are momentum-matching cells and empty cells.

The semicircular arcs are made up of separated function cells of FODO or "doublet" structure, Q_F B Q_D B. The phase advance $\mu = \pi/2$ is chosen because it gives large transition energy, which aids in reducing the proton rf voltage. The horizontal dispersion in the normal cells is brought to zero in three half-cells, the first empty of bending magnets and the second and third with different total bending and magnet placement than obtains in normal cells.

In the electron ring, following the momentum matching section and preceding the insertion, there are two shortened empty cells, which are needed to equalize the circumference of the proton and electron rings. (E_p/E_e must be a constant in this design.)

The long insertions are the most difficult parts of the system to design. The low-β's (needed for high luminosity) causes the beams to diverge rapidly as they leave the interaction point. Adequate space for experiments requires a magnet-free region of at least $\pm$ 10 m, which value has been adopted in this design, and, consequently, both beams must pass through some common quadrupoles unless a system with septum magnets is employed. This design uses common quadrupoles.

The present design can best be understood from Figure 1. The focussing pattern transforms the small β values at the interaction point to the matched values appropriate to the normal cells. At the same time vertical dispersion from the vertical bends is eliminated. In the electron insertion this is done simply by having no quadrupoles along the dog legs consisting of the four bends B1, EB2, EB3, and EB4 and by their bilateral symmetry. In the proton insertion the section between B1 and PB2 is reflection-symmetric about its center. The dispersion is constrained to be zero in the center, and this causes it to be zero everywhere outside of the section B1 - PB2.

The long length of the proton insertion arises largely from the need to separate the beams vertically without too much bending in the electron path, which would consume rf power and spread that beam vertically.

3. Engineering Considerations

The design example parameters were used for a first look at such engineering implications as the feasibility, power, cost and size of the equipment. A few of the initial findings are set forth here.

A possible arrangement of the ring enclosure, proton injector and the beam transfer lines is shown in Figure 2. Present thinking leans toward excavation by tunneling with above-ground service buildings, somewhat as planned for CERN II.

The magnets for the proton ring appear somewhat formidable. As shown in the beam profiles of Figure 1, the beam amplitudes in many of the proton magnets are quite large, such as $\pm$ 17 cm in quadrupoles PQ3 and PQ4 near the interaction region. Initial estimates indicate that the field precision $(\Delta B / B_{max})$ in these quads needs to be of the order of 10^{-4} to 10^{-5} integrated for any ray through the quad. This precision is considerably better than is customarily encountered in synchrotrons and is comparable to that of precise spectrometer magnets. The closely-adjacent e^+e^- beam lines pose severe design restraints on these magnets. A possible way of achieving these requirements for the high-quality-field quadrupoles is to arrange the pole tips and conductors on orthogonal hyperbolas. This can be thought of as a conformal transformation of the familiar picture-frame and septum magnets. To achieve the precision desired, an array of trim conductors arranged along the pole tip or vacuum chamber is anticipated. It is not yet clear how one would "tune" the multitudinous trim circuits. Each PQ4 quadrupole will weight about 50 tons, so these are large magnets. The magnets and associated power supplies for the arc sections, while requiring careful design, appear relatively straightforward compared to the foregoing quadrupoles.

The rf system for the e^+e^- ring will develop about 100 MV per turn at a power output of about 4.5 MW. To conserve ring circumference and obtain high efficiency, we are considering use of high-shunt-impedance side-coupled cavities of the type developed for the Los Alamos Meson Physics Accelerator, but operating at 330 MHz. The proton ring requires only a fraction as much voltage per turn. However, as mentioned elsewhere, the phase-jitter tolerance may be exceedingly tight.

Vacuum requirements have not yet been defined, but are assumed to be of the order of 10^{-9} to 10^{-10} torr.

III. TOPICS REQUIRING FUTHER STUDY

In this section we select a few of the important questions which must be resolved before a PEP system can be built, and discuss, with regard to them, our present state of knowledge and future research plans.

1. Beam Dynamics

Considerable attention must be given to the subject of coherent instabilities. Of special concern, for a tightly bunched beam, is the beam-cavity interaction. To avoid trouble, one must limit the product of the shunt impedance and the quality factor: QZ_{ℓ}. Also of special concern is the head-tail transverse instability, which will necessitate careful control of the chromaticity. Resistive wall instabilities may be greatly reduced (in a single-bunch mode) by proper choice of ν-value. Introduction of nonlinearities, so as to supply adequate Landau damping, must be balanced against the requirements on field purity (probably set by the conditions needed for proper injection), and will have to be carefully studied.

A major uncertainty in the PEP project is the value of the electron-beam density above which the proton beam density becomes unacceptably low or the lifetime becomes unacceptably short (of the order of 10^4 sec). In the machine example of Sec. II we adopted the "conventional" limit on electron density $\Delta\nu = 0.025$, while being very conscious of the fact that the basis for this limit is insecure. In fact, experimental information from the ISR shows only that at $\Delta\nu = 3.5 \times 10^{-4}$, lifetime is adequately long; there is no information concerning proton-beam lifetime at larger $\Delta\nu$ values. Computational studies give an upper limit to $\Delta\nu$ of the order of 2.5×10^{-2}, but have not been adequate to establish the lifetime at smaller values of $\Delta\nu$. Some semianalytic estimates of Arnol'd diffusion have been made by E. Keil, who employs Chirikov's formulation of the theory, and deduces that $\Delta\nu \simeq 3 \times 10^{-3}$ may be needed in order to have a 10^4 sec lifetime.[4] This work is rather speculative and far from being rigorous, but it is suggestive. We are undertaking further computational studies, on one of the fastest computers available, which incorporate the complicating aspects of very low-β crossing regions as well as small crossing angles. (We are including the dependence of beam size and of β upon azimuthal distance, as well as the long-range forces experienced outside a beam.) In addition to the work, and to analytic studies, we plan to do experiments on existing storage rings--employing nonbeam-induced nonlinear perturbations--to study beam lifetime as a function of perturbation, and as a function of energy oscillation (which is a necessary consequence of the bunched beams of PEP).

The above work is addressed to the weak beam-strong beam limit; a strong beam-strong beam interaction could result in an even lower limit. We hope to obtain information from the SLAC storage ring SPEAR on this difficult subject.

2. Radio-Frequency Noise

In order to maintain a proton beam tightly bunched for long times (of the order of 10^4 sec), it is necessary to keep the spectral density of noise in the rf system at a sufficiently low level. Feedback systems, both within the rf system itself and from the beam, may be employed in order to reach the requisite low noise figure. It will be necessary to do careful design studies and model studies in order to demonstrate that a very high-power rf system can be built to the required tolerance. Experimental investigations are being carried out using the LBL Bevatron.

3. Injection Energy and Injector

The machine model of Sec. II could be filled with protons from an injector with an energy as low as 3 GeV having normalized emittances $\tilde{\epsilon}_x = 0.01$ cmrad, $\tilde{\epsilon}_y = 0.005$ cmrad, and $\tilde{\epsilon}_\ell = 2.30$ cm, with 1.7×10^{11} particles per turn (of the storage ring). In order to reach the parameters of Table I we might stack 6 turns horizontally and 2 turns vertically with a dilution factor of only 1.35. A detailed study is needed of the injector and the injection process. The above beam parameters are feasible (being those of the PS with a modest safety factor), but other beam parameters may well be more optimum. Furthermore, a cost optimization must be performed in order to fix the injection energy.

4. Lattice

In the machine example of Sec. II, a co-linear interaction region for head-on collisions was used. This choice minimizes the total number of stored protons required and provides for a large-solid-angle solenoid detector; however it imposes the restriction that the proton beam must be bunched with bunch length comparable to the value of β at the interaction region. Such bunching requires a large rf voltage, and makes the system critically dependent upon the effects of noise described in Topic 2 above.

Use of a crossing angle between the colliding beams would relieve the requirements on the proton rf system and offer a decoupling of the electron and proton lattices which might prove attractive even though the instantaneous proton current and the proton number would be higher. Furthermore it might allow longitudinal stacking and a corresponding reduction in aperture requirements. Crossing angles are under study.

In the electron ring of the design example, the density of the electron beam in the zero-dispersion interaction region is held down by using comparatively low betatron tunes with correspondingly low γ_T. This results in poor momentum compaction which requires an uncomfortably high rf voltage to contain quantum fluctuations. This problem could be alleviated by using nonzero dispersion at the interaction region to achieve the necessary transverse density and raising γ_T.

Furthermore, the interaction-region β-values in the electron ring must be diminished to achieve the maximum potential luminosity in e^+e^- collisions.

Other subjects for further study are (a) possible reduction of the proton beam size in the insertion, (b) possible reduction in the (rather long) insertion length, (c) a lattice with special features to enhance detection of reaction products (such as a beam waist at a point of large dispersion), (d) more interaction regions within one insert, (e) provision for p-p collisions (clearances are not adequate in the present example), (f) parameter selection so that an enlarged luminosity can be achieved at a reduced electron energy, and (g) variation of parameters so as to achieve cost optimization.

In addition, study must be made of the tolerances on field purity (especially in the large-aperture quadrupoles of the insertion), as well as on the rf system.

5. Magnets

Initial cost estimates indicate that the magnets (particularly those of the proton ring) together with their associated power supplies, electrical distribution and water cooling systems are the dominant cost of the total facility. We therefore plan to look carefully at possible means for reducing the magnet apertures. We also plan to explore the possible use of superconducting magnets in order to reduce the cost of the magnet system and its operation, as well as to allow higher energy protons.

IV. ACKNOWLEDGMENTS

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TABLE I. Beam and Performance Parameters

		Proton	Electron	
Momentum	P/c	72	15	GeV/c
Number of Particles	N	2.04×10^{12}	3.08×10^{12}	
Emittances[1] (normalized)	$\tilde{\epsilon}_x$	0.081	15	cm-rad
	$\tilde{\epsilon}_y$	0.0135	2.5	
	$\tilde{\epsilon}_\ell$	2.835	527	
Luminosity	$\mathcal{L}$	0.57×10^{32}		$cm^{-2} sec^{-1}$
Interaction Point Values:				
Crossing Angle	2δ	0.0		
Free Drift Length	L_I	±10		m
Beta Function ($\beta^*_x = \beta^*_y$)	β^*	0.25	0.20	m
Dispersion Function	X^*_{eq}	0.0	0.0	m
RMS Beam Sizes at Crossing:				
Horizontal	σ^*	0.0663	0.0413	cm
	$\sigma^*_{x'}$	2.654	2.064	mrad
Vertical	σ^*_y	0.0271	0.0168	cm
	$\sigma^*_{y'}$	1.084	0.842	mrad
Longitudinal	σ_ℓ	9.0	2.95	cm
	$\sigma_{\beta\gamma}$	0.0442	29.8	
Effective Sizes at the Entrance to the Quadrupole Nearest the Crossing Point[2]	X_Q	6.49	9.46	cm
	Y_Q	1.94	2.87	cm

1 $\tilde{\epsilon}_x = xx'\beta\gamma$ where the ellipse of area $\pi\epsilon_x$ encloses 95% of particles of a Gaussian distribution, hence $x = \sqrt{6}\ \sigma_x$. Likewise with $\tilde{\epsilon}_y$ and $\tilde{\epsilon}_\ell$. Note that $\tilde{\epsilon}_\ell \equiv (\delta\ell)(\delta\beta\gamma)$.

2 The effective size is taken as $\sqrt{6}\ \sigma$ for protons, 6.5 σ for electrons.

TABLE II. Lattice Parameters

		Proton	Electron	
Average Radius	R	314.2	314.2	m
Average Radius of Circular Arcs	R_n	197.4	198.4	m
Magnetic Radius	ρ	116.25	120.37	m
Magnetic Field in Cells	B_o	20.64	4.157	kG
Quadrupole Gradient in Cells	G	224.	81.6	kG/m
Insertion Length[1]	S	327.	203	m
Cell Length	L_c	20	35	m
Number of Normal Cells	$2 \times n$	60	32	
No. Momentum Match Sections[2]	$4 \times n_\mu$	4	4	
No. Empty Cells[3]	$4 \times n'$	0	4 x 2	
Length Empty Cells	L_{CE}	-	29.9	m
Number of Insertions	N_s	2	2	
Number of Superperiods	N_p	2	2	
Vertical Separation Between Rings	H	1.14		m
RF System, Peak Volts/Turn	V	24	90	
Power Radiated by Beam	P_b	-	2.8	MW
Transition γ	γ_t	13.9	9.1	
Cell β-Function: Maximum	β	32.9	59.5	m
Minimum		6.9	10.4	m
Cell Off-Momentum Function: Maximum	x_{eq}	1.47	4.14	m
Minimum		0.76	1.98	m

Table Continued

TABLE II. (Continued)

Slected Effective Sizes X x Y (full energy)			
Cell QF	1.86 x 0.35	4.63 x 0.78	cm x cm
QD	0.85 x 0.76	1.93 x 1.88	cm x cm
Maxima in Insertions:	12.5 x 10.5	17.3 x 11.7	cm x cm
	14.7 x 7.3	11.6 x 17.2	cm x cm

1 Distance to first cell quadrupole.

2 Each momentum match section consists of 3 half-cells: one empty and two partly filled with bending magnets.

3 These empty cells are 5 m shorter than normal cells.

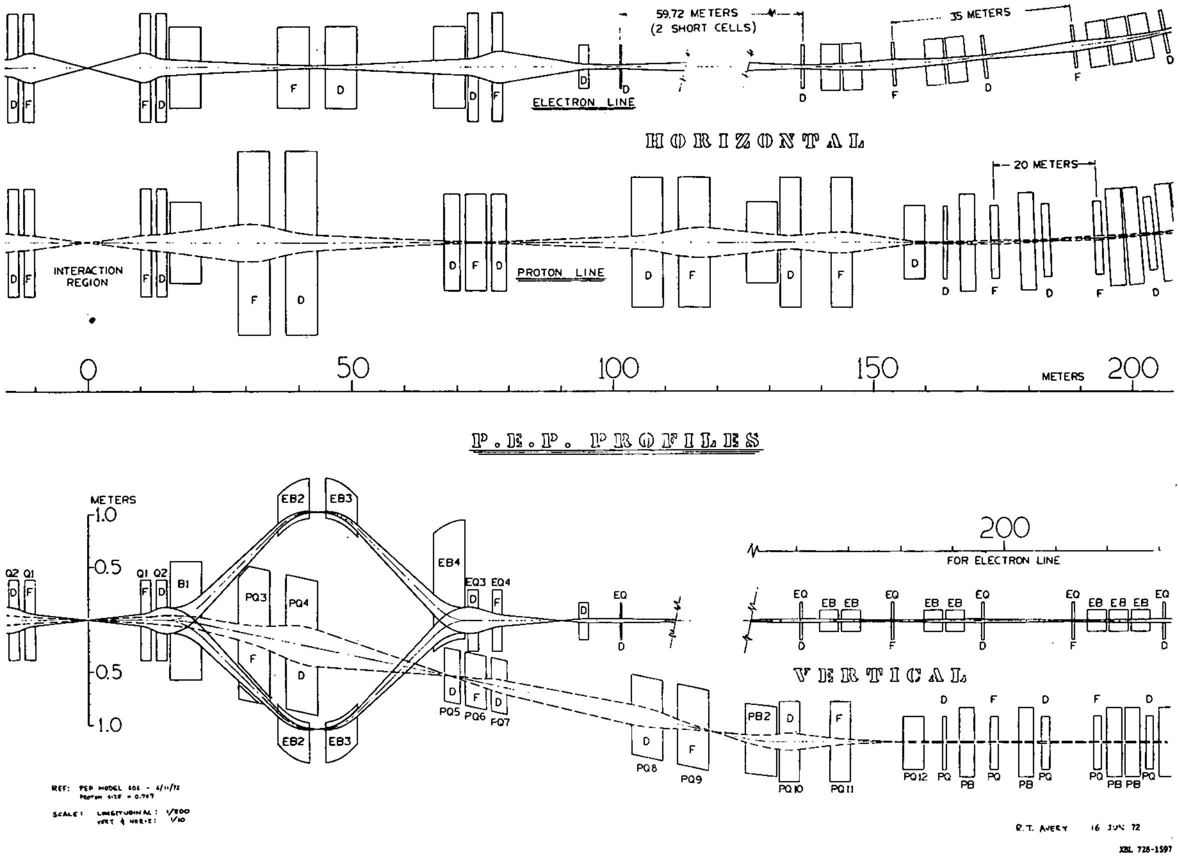

Fig. 1. Profiles for a PEP machine design example. The scale is longitudinally 1/200, and horizontally and vertically 1/10. Bending magnets are marked with B, quadrupoles with Q or with F (focussing in that plane) and D (defocussing in that plane). The electron line is often indicated by E, the proton line by P.

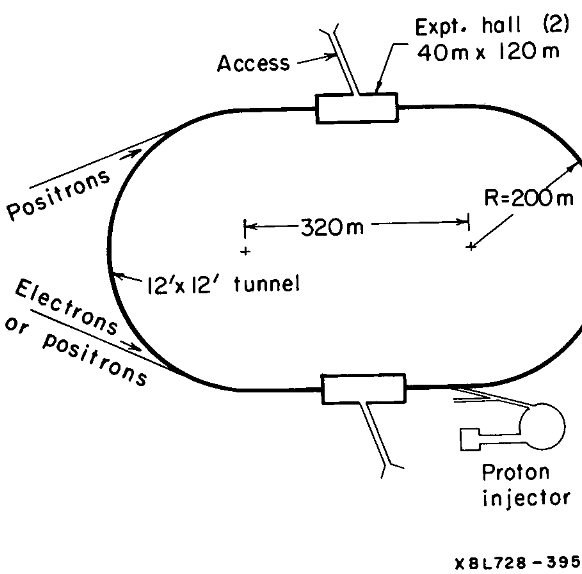

Fig. 2. General arrangement for the machine example of Sec. II.